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SIMULATING RICE YIELDS UNDER CLIMATE CHANGE SCENARIOS USING THE CERES-RICE MODEL

P. OTENG-DARKO, N. KYEI-BAFFOUR and E. OFORI
P. O.-D.: CSIR-Crops Research Institute, P. O. Box 3785, Kumasi, N.K.-B. and E.O: Department of Agricultural Engineering, KNUST, Kumasi, Ghana
Corresponding author: patamankwaa@yahoo.com

ABSTRACT

The effects of climate change on rice production and yield cannot be overlooked in finding measures to increase production and yield. The CERES-Rice (Ver. 4.0) model was calibrated and evaluated for use in simulating rice yields under different climate change scenarios in Ghana using data from the Anum Valley Irrigation Project. Eighteen years of weather data (1989-2006) was used to run the model. The model was found to be sensitive to climatic parameters (temperature, CO_2 concentration, solar radiation and rainfall) and had various effects on rice. Simulated rice yields were sensitive to weather years as there was 13% less yield of rice in 1999 compared with 2001. Increases or decreases of temperature by 4 ^{o}C from the maximum or minimum, decreased rice yields by 34% as compared to base scenario of 2006. Similar change in temperatures along with an increase in solar radiation by 1 MJ m^{-2} day^{-1}, decreased rice yield by 32% compared to base scenario. On the other hand, the same changes in temperature from the maximum and minimum, together with an increase in CO_2 concentration by 20 ppm from the standard CO_2 concentration of 330 ppm, led to a reduction in rice yield of 33%. Simulations demonstrate that the effects of planting dates cannot be overlooked in finding measures to increase rice yield under climate change mitigations. The effects of climate change on rice yield of will depend on the actual patterns of change in rice growing areas. However, the negative impacts can be averted through appropriate measures such as changes in agronomic practices, development of more temperature tolerant rice varieties and effective training of farmers.

Key Words: Carbon dioxide, mitigations, sensitive, scenario, solar radiation

RÉSUMÉ

Les effets du changement climatique sur la production et le rendement du riz ne peuvent être négligés lors de la prise des mesures pour accroître la production et le rendement. Le modèle *Ceres-Rice* (ver. 4.0) était calibré et évalué pour la simulation des rendements du riz sous différents scenarios de changement climatique au Ghana en utilisant des données fournies par le projet d'irrigation de la vallée d'Anum. Les données climatiques couvrant 18 ans (1989-2006) étaient utilisées dans ce modèle. Le modèle était trouvé sensible aux paramètres climatiques (température, concentration en CO_2, radiation solaire et pluviométrie) et présentait des effets variés sur le riz. Les rendements simulés de riz étaient sensible aux années climatiques étant donné 13% de diminution du rendement du en 1999 en comparaison avec 2001. Des augmentations ou diminutions de la température de 4 ^{o}C du maximum ou minimum, avaient induit une diminution de 34% de rendements comparée au scenario de base en 2006. Des changements similaires de température avec un accroissement de la radiation solaire de 1 MJ m^{-2} jour^{-1}, avait induit une diminution du rendement du riz de 32% en comparaison avec le scenario de base. D'autre part, les mêmes changements en température du maximum au minimum avec une augmentation de la concentration de CO_2 de 20 ppm de la concentration standard de CO_2 de 330 ppm, avait entrainé une réduction de rendement du riz de 33%. Les simulations démontrent que les effets des dates de plantation ne peuvent pas être négligés dans la recherche des mesures pour accroitre le rendement du riz dans la mitigation des effets de changement climatique. Les effets du changement climatique sur le rendement du riz dépendront des approches actuelles de changement dans les milieux d'exploitation rizicole. Par ailleurs, les impacts négatifs peuvent être évités par des mesures appropriées, notamment les changements des pratiques agronomiques, le développement des variétés de riz plus tolérantes à la température et une formation effective des fermiers.

Mots Clés: Dioxyde de carbone, mitigation, sensible, scénario, radiation solaire

INTRODUCTION

Rice is one of the main staple foods in the world and has also become the second most important staple food in Ghana. Policy strategies over the years have sought to promote rice production to address food security and poverty reduction issues. But rice production is threatened by the effects of climate changes (Amien *et al.*, 1996). Thus, the effects of climate change on rice production and yield cannot be overlooked in finding measures to increase production and yield. According to Shewmake (2008), with the kind of large uncertain shocks to food and water security that climate change is likely to bring, being able to address vulnerability becomes a useful tool in poverty reduction especially in developing countries.

Climate change can affect crop yield in a variety of ways. According to Rosenzweig and Hillel (1995), air temperature and atmospheric CO_2 concentration will directly affect plant growth through photosynthesis and respiration. Higher CO_2 concentration in the atmosphere, to a certain extent, enhances photosynthesis. Plant growth is very sensitive to temperature. Often a difference of a few degrees in temperature leads to a noticeable change in growth rate (Rosenzweig and Hillel, 1995). Higher air temperatures will increase rice plant respiration rate and reduce net photosynthesis, hence, reducing plant yield (Rosenzweig and Hillel, 1995). Rice is particularly responsive to increased carbon dioxide concentration. High carbon dioxide concentrations also increase water use efficiency (Hunsaker *et al*, 2000: Seraj *et al*, 1999: Hakala *et al*, 1999). In addition, high carbon dioxide levels increase plants' resistance to salinity and drought, and increase nutrient uptake (Kafkafi, 1997; Kaya *et al.*, 2001).

Research done in important rice growing areas around the world show that rice yields are vulnerable to climate change (Rosenzweig and Iglesis, 1994; Mohandrass *et al.*, 1995; Ferrero and Nguyen, 2004). However, estimated impacts of climate change on rice yield are highly variable and depend on the rice/yield model used, the choice of climate change scenario, the region, the growing season and other factors (IPCC, 2000). In Bangladesh, the impact of climate change on high yield rice varieties was studied by Karim *et al.* (1994), using the CERES-Rice model and several scenarios and sensitivity analysis. They found that high temperatures reduced rice yields in all seasons in most arid locations; the detrimental effects of temperature rise more than offsets the positive effect of increased CO_2 levels. Increased CO_2 levels actually increases rice yield. Similar experiments in India reported by Sinha (1994), found that higher temperatures and reduced radiation associated with cloudiness caused spikelet sterility and reduced yields to such an extent that any increase in dry matter production proved to be of no advantage in grain productivity. Similarly, Amien *et al.* (1996) found that rice yields in east Java could decline by 1% as a result of increases in temperature.

The objective of this study was to evaluate the CERES-Rice model for its ability to simulate rice yield under various climate change scenarios and estimate the potential yield of rice under different climate change scenarios.

MATERIALS AND METHODS

Study area. The yield simulations and analysis were done using data from the Anum Valley Irrigation Project. It is located at Nobewam in the Ejisu Juaben District of the Ashanti Region of Ghana. It lies on latitude 6^{o}37' and longitude 1^{o}18' (Anum valley project report, 1999 unpublished). The project has a total potential of 140 hectares, out of which 90 hectares have been fully developed. The project is divided into two areas, A and B. Area A has a net area of 40 hectares and area B has 100 hectares. Two rivers supply irrigation water to the project. The Anum River from which the project gets its name, serves Area A, while its tributary the Owerri River serves Area

B. The type of irrigation practiced is surface irrigation with basins. Each basin covers an area of 50 m x 20 m.

Data collection. Since the Anum Valley Irrigation Project does not have a meteorological station, climate data were sourced from the Bobiri Forest Reserve, which was closer to the project site (Nobewam lies on latitude $6^o37'$ and longitude $1^o18'$, while the Bobiri Forest weather station lies on latitude $6^o41'$ and longitude $1^o21'$). Data on the soils were obtained from the project report. These data included bulk density, soil type, total soil nitrogen, soil pH, percentage sand, clay and silt; and electrical conductivity. Data on the variety of rice grown (*Sikamo*) was obtained from the CSIR- Crops Research Institute. Data on yield (Table 3.1) were obtained from the project report. The project's average yield was 3.87 t ha^{-1}.

Model description. The Crop Estimation Resource and Environment Synthesis (CERES) - Rice model was one of the models developed through the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project which can predict growth and yield of rice varieties under all agro- climatic conditions (Mathauda *et al*., 2000). The latest CERES-Rice model version 4 is embedded within DSSAT 4.0, which was developed through collaboration between scientists at the University of Florida, the University of Georgia, University of Guelph, University of Hawaii, the International Centre for Soil Fertility and Agricultural Development, Iowa State University and other scientists associated with the International Consortium for Agricultural Systems Applications (ICASA). The Decision Support System for Agrotechnology Transfer (DSSAT) is a software package integrating the effects of soil, crop phenotype, weather and management options that allows users to ask what if questions and simulate results by conducting, in minutes on a desktop computer, experiments which would consume a significant part of an agronomist career (Hoogenboom *et al.*, 2003).

Model calibration and validation. Parameters were adjusted to suit the local conditions. Cultivars, climate and soil data were defined and substituted for use by the model. This was done using XBuild. The purpose of the XBuild programme is to provide more effective tool to access all of the functionality of the crop model. It allows users to specify any combination of management options for simulation for purpose of validation (comparison with observed data), seasonal analysis, crop rotations, and spatial analysis that are available in DSSAT. Some examples of model validation techniques include:Face validation, Historical data validation,Accepted approach methods, Validation derived from empirical data and Validation based on theoretical derivation. The percentage relative difference (R.D.%), which is an example of validation based on theoretical derivation, was used to conduct the validation. Simulated yield results were compared with measured project yield and validations were done using the percentage relative difference (R.D. %) method:

$$R.D.\% = \frac{\text{average predicted value - average field value}}{\text{average field value}}$$

According to Kulatelake (1993), an R.D. less than 30% signifies an efficient model prediction. Here, the lesser the R. D. % value is below 30%, the greater the prediction accuracy. A zero percent relative difference will, therefore, indicate that predicted values match field values decimal place for decimal place.

A model reproduces experimental data perfectly when: α (slope of linear relation between simulated and observed values) is 0, β (intercept of linear relationship between simulated observed values) is 1, R^2 (adjusted linear correlation coefficient between simulated and observed values) is 1, RMSE (root mean square error) is 0, and D-index (index of agreement) is 1.

Generation of climate change scenarios. A climate change scenario refers to a representation of the difference between some plausible future climate and the current (usually represented by observations) or control climate (represented by a climate model). Trends in the observed time series of temperature and rainfall, during the period 1989 to 2006 were analysed by Weatherman and recalled for use by the CERES-Rice model.

Yield simulations. Experimental data file was created using XBuild. The file contained details of the experiment (field characteristics, soil analysis data, initial soil water and inorganic nitrogen conditions, seedbed preparation and planting geometries, irrigation and water management, fertiliser management, organic residue applications, chemical applications, tillage operations, environmental modifications, harvest management), simulation controls, and treatment combinations. These data were saved and imported into the rice model. The run icon was selected to initiate the running of the model. Upon initiation, created climate, crop and soil files along with the experimental files, were recalled for the simulations. Simulations were then run for different climatic scenarios and management options; after which analysis was made to select the best simulated results.

Estimating rice yield change under climate change scenarios. Environmental modifications were made to the created XFiles. By using the environmental modification tool of the CERES-Rice model, minimum and maximum temperatures were increased by 4°C, solar radiation by 1MJ m^2 d^{-1} and CO_2 concentration by 20 ppm. Actual yield data was compared with simulated results to determine the rice yield change under the various climate change scenarios simulations.

Input parameters. The following were the input data used for the validation and running of the model (unless otherwise stated for a particular scenario): Plot size – 50 m x 20 m (0.1 ha), Top soil – Loamy Sand, Bulk Density – 1.20 g cm^{-3}, Soil pH – 5.78, Climate data – daily weather data (maximum and minimum temperatures, rainfall and solar radiation) from 1989-2006 from the Bobiri Forest Reserve; CO_2 concentration – 330 ppm; Planting method – transplanting; Planting depth – 5 cm; Irrigation – no water stress; Fertiliser amount – 90 kg N ha^{-1}; and Harvest – at maturity (120 days). For validation purposes, the model outputs were tested using a minimum data set (MDS) sourced from the Anum valley Irrigation Project (through questionnaire administration). A continuous flooding treatment (no water stress) with 90 kg N ha^{-1} for rice, was used as the 'base or standard scenario'. The experiment tested the response of varying planting dates and environmental modification on rice. At present, only one rice cultivar— *Sikamo* (TOX 3108) accounts for all the rice production under the project. IR36, a cultivar which is close to *Sikamo* (TOX 3108) in terms of phenology and genetics was chosen to replace *Sikamo* (TOX 3108) and set as the default for all yield simulations. The performance of the CSM CERES-Rice under potential production conditions (no water stress) with environmental modifications was tested using the same prevailing conditions in the fields by simulating the yield under localised climatic conditions. The model was run using 18 years of weather data (1989 to 2006) from the Bobiri Forest Reserve in the Ashanti Region. This run gave an average rice yield of 4.45 t ha^{-1}.

The climate change simulations were accomplished by using the Environmental Modification section of XBuild (Experimental file) of the CERES-Rice model. After calibration, evaluation and validation of the crop model, the CSM CERES-Rice v4 was run to determine the impacts of climate change on rice yield. The model

TABLE 1. Relative difference between actual and simulated rice yields in Ghana using CERES-Rice model

Year	Actual yield (t ha^{-1})	Simulated yield (t ha^{-1})	Relative difference (%)
1989	NA	4.57	NA
1990	NA	4.40	NA
1991	NA	4.79	NA
1992	3.3	4.23	28.18
1993	4.0	4.40	10.00
1994	4.5	5.19	15.33
1995	4.0	4.32	8.00
1996	3.9	4.45	14.10
1997	4.0	4.39	9.75
1998	3.8	3.96	4.21
1999	4.0	5.21	30.25
2000	4.0	4.22	5.50
2001	4.2	4.37	4.05
2002	4.0	4.97	24.25
2003	4.0	4.25	6.25
2004	4.0	4.33	8.25
2005	3.5	4.20	20.0
2006	3.6	4.43	23.1

was run with 18 years observed weather data. Environmental modifications were made according to the climate change scenarios and predictions given in Table 2. These climate change scenarios were used as treatments to study the impacts of each modification in CO_2, minimum and maximum temperature and rainfall on rice grain yield. In simulating rice growth, irrigated conditions were applied by using weather data from both normal and dry years. Environmental modifications were made according to the climate change scenarios and predictions given in Table 2 and used as treatments to run simulations. Temperatures were maintained (base/current value) and increased or decreased by 4 ^oC; solar radiation was maintained, decreased or increased by 1MJ m^{-2} d^{-1}; CO_2 was maintained or increased by 20 ppm.

The sensitivity of yield simulated by CSM-CERES-Rice to climatic parameters was tested for the continuous flooding treatment.

RESULTS AND DISCUSSION

Crop model validation and evaluation under local climatic conditions. Results (Fig. 1) showed that the simulated yields of the rice crop were sensitive to various weather years. The differences in yield between the actual and the simulated values were assumed to be as a result of agronomic and management practices in the farmer fields. The same input parameters were used to run the model from 1989 to 2006. Table 1 gives the simulated results and the ensuing RD% and RMSE between the simulated and actual results.

There existed an undulating trend (Fig. 1) in simulated rice yield for the consecutive years and it was lowest for 1998. The years 1999 and 1994 recorded the highest simulated yields of 5.21 and 5.19 t ha^{-1}, respectively. The highest relative difference of 30.25% was recorded in 1999. Relative differences ranged from 4.21% (in 1998) to 30.25% (in 1999). The differences can be attributed to the fact that the project has been yielding below its average targeted yield. GIDA has targeted an average yield of 7.2 t ha^{-1} for *Sikamo* on its projects.

An average R.D. % of 12.28 (<30%) indicates a good correlation between simulated yields and actual yields. Since the model was run using prevailing field conditions, but does not account for yield losses due to harvest practices, pest and diseases and lodging, it can be concluded that variations between actual and simulated

TABLE 2. Sensitivity of simulated yield of rice to temperature, CO_2 concentrations and solar radiation with continuous flooding in Ghana

Maximum temperature (^oC)	Minimum temperature (^oC)	CO_2 Concentration (ppm)	Solar radiation (MJ m^{-2} d^{-1})	Simulated yield (t ha^{-1})	Growth duration (days)
Base value	Base value	330	Base value	4.45	121
Base value	Base value	+20	Base value	4.58	121
Base value	Base value	330	Increase	4.69	121
Base value	Base value	330	Reduction	4.25	121
Increase	Increase	330	Base value	2.78	110
Increase	Increase	+20	Base value	2.81	120
Increase	Increase	330	Increase	3.03	110
Increase	Increase	330	Reduction	2.56	110
Increase	Increase	+20	Increase	3.17	110
Reduction	Reduction	330	Base value	5.62	142
Reduction	Reduction	+20	Base value	5.56	143
Reduction	Reduction	330	Increase	5.93	143
Reduction	Reduction	330	Reduction	5.42	145
Reduction	Reduction	+20	Reduction	5.49	143
Reduction	Reduction	+20	Increase	5.32	143

ppm = parts per million

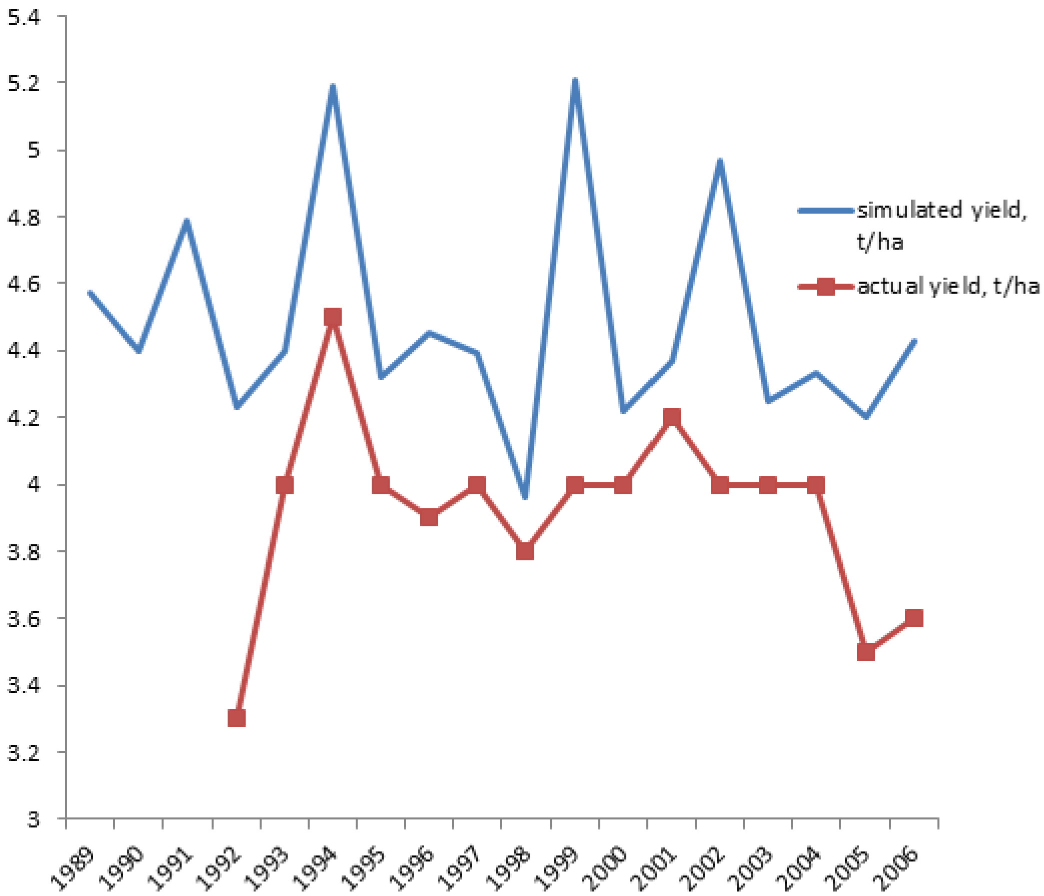

Figure 1. Simulated and actual yield from 1989-2006 in Ghana.

yields is adequately accounted for. The yield differences can also be attributed to soil degradation caused by unsustainable agronomic practices at the Anum Valley rice fields.

Simulated rice yield scenarios. The results showed that as compared to rice yield (4.45 kg ha^{-1}) for the standard treatment (no changes in maximum and minimum temperatures, solar radiation and CO_2 concentration), the yield was 26% higher for the decrease in maximum and minimum temperature by 4ºC, but 60% lower for the increase in maximum and minimum temperature by 4ºC. Increased temperatures decreased growth duration by 11 days, while decreased temperature increased growth duration by 21 days. Decreasing temperatures and increasing solar radiation by 1MJ m^{-2} day^{-1}, increased the rice yield by 33% and growth duration by 22 days showing the interactive effect of temperature and solar radiation. With a decrease in temperature, vegetative and grain filling periods became longer and produced higher yields, but with an increase in temperature the reverse was observed.

The longest crop growth period of 145 days was recorded for reductions temperatures and reduction in solar radiation by 1MJ m^{-2} day^{-1}. Elevated CO_2 has been reported to promote dry-matter production in rice more than grain yield through the enhancement of net assimilation rate and leaf area, even if temperatures remain substantially high (Imai and Murata, 1979). At elevated CO_2, light intensity positively affects photosynthesis and increased temperatures promotes both photosynthesis and leaf area (Imai and Murata, 1979). The results showed that, compared to average rice yield (4.45 t ha^{-1}) for the 90 kg N ha^{-1} treatment, the yield was 20.82% higher for the decrease in temperatures, but 60.01% lower when temperatures were increased. Increased temperature decreased growth duration by 11 days, while decreased temperature increased growth duration by 22 days.

Decreasing both maximum and minimum temperatures and increasing solar radiation by 1MJ m^{-2} day^{-1}, increased the rice yield by 24.96% and growth duration by 23 days, showing the interactive effect of temperature and solar radiation. Increasing temperatures by 4^{o}C, CO_2 concentration by 20 ppm and solar radiation by 1 MJ m^{-2} d^{-1} decreased yield by 40.37%; while decreasing temperatures by 4^{o}C, solar radiation by 1 MJ m^{-2} d^{-1} and CO_2 concentration by 20 ppm increased yield by 18.94% and reduced growth duration by 7 days. This is because lower temperatures reduces plant respiration rate and increases net photosynthesis; whereas high CO_2 concentration increases water use efficiency and nutrient uptake thereby enhancing photosynthesis which eventually increases grain filling and yield (Allen, 1991). The maximum yield reduction of 73.28% occurred when maximum and minimum temperatures were increased by 4^{o}C with no increase in CO_2 concentration and a 1 MJ m^{-2} d^{-1} decrease in solar radiation. Higher temperatures increases rice plant respiration rate and reduce net photosynthesis hence eventually reducing yield.

The rice crop model generally predicted yield reductions due to possible climate change in the future. The increased in temperatures, irrespective of whether CO_2 concentration was increased or not, seemed to have more adverse effects on the rice yield. Closer investigations of model processes and more testing of the models would be required to better examine the sensitivity to various climatic parameters and to evaluate adaptation scenarios to climate change in the future.

The CERES-Rice model was sensitive to the various weather years. The sensitivity tests indicated the year 1994 and 2002 were good for the rice crop. Since the model was run using prevailing field conditions but did not account for yield losses due to harvest practices, pest and diseases and lodging, it can be concluded that variations between actual and simulated yields are adequately accounted for and that the model can be used under local climatic conditions in Ghana.

CONCLUSION

The impacts of climate change on rice yield will depend on the actual patterns of change in rice growing areas. However, these impacts can be averted through the concerted efforts of agricultural research and policies aiming to improve rice varieties and accompanying management strategies.

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